This section presents the work process, describes the simulation tool utilized, defines airfield and airspace capacity and delay, and acquaints the reader with key variables that affect Bay Area airport and airspace capacity and delay.

2.1 WORK PROCESS

Figure 2-1 presents the work tasks that may be grouped into four steps:

- **Model Verification.** To ensure that the simulation model provides accurate results, SIMMOD capacity and delay results for 1999 are compared and calibrated against actual performance at the three Bay Area airports.
- **Demand Management Alternatives.** The impact of various demand management and technology improvement options at SFO are analyzed to minimize delay for years 2010 and 2020.
- **New Runway Alternatives.** Eleven (11) combinations of various runway alternatives at SFO and OAK are analyzed for years 2010 and 2020.
- **Summary of Results.** Delay and capacity results for all simulation runs are tabulated and key differences are highlighted.

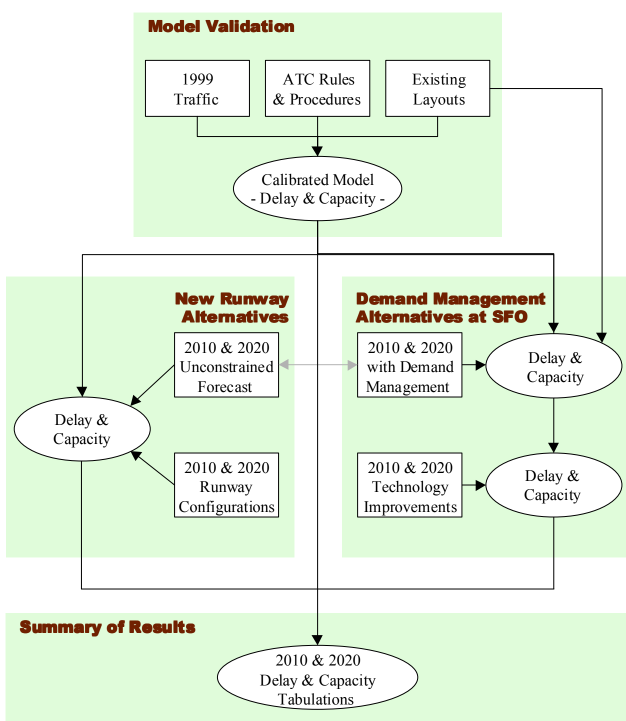

Figure 2-1 Regional Airport Delay and Capacity Study Process

2.2 SIMULATION MODELING SOFTWARE

Analysis of airport capacity and delay is performed using SIMMOD, an FAA-approved computer program. This program is capable of capturing all the interactions between runways at multiple airports and the airspace procedures, thus assessing how existing and proposed runways will handle the forecasted level of aircraft operations in the future.

2.2.1 Description of Software

SIMMOD is an aircraft movement simulation model developed and sponsored by the FAA. The model is graphic and user friendly with a flexible output analysis and reporting module. There is no limit to the number of airports or size of terminals and airspace, so it is ideal for modeling the Bay Area's multi-airport environment. SIMMOD input can be grouped into the following three categories:

- *Airfield-related*: includes physical layout of airports and operational parameters such as gate, taxiway, and runway structure; airlines' use of gates; taxiway routings between gates and runways; departure lineup strategies; and aircraft landing and takeoff characteristics.
- *Airspace-related*: includes airspace routings; airspace sectorization; airspace separation standards including wake turbulence; arrival and departure procedures, and required separations; metering and flow constraints; and strategies for resolving potential conflicts.
- *Simulation event*: allows the user to specify the aircraft departure and arrival (demand) schedules for existing and future conditions and the desired changes in operating conditions, including runway use configurations, terminal routing plans, and flow and metering constraints.

SIMMOD models airports and airspace networks as a series of nodes connected by links. A node is a point in a coordinate system where SIMMOD evaluates an aircraft's position with respect to other aircraft. A link defines the path between two nodes. Aircraft move from one node to another only along a defined link. SIMMOD maintains airfield (ground) and airspace nodes as separate groups. The flight schedules and the simulation clock work together to process SIMMOD events in the proper sequence.

SIMMOD simulates the movement of each aircraft on the ground and in the air. SIMMOD has extensive statistical reports on aircraft delays in the air, on the ground, and at gates. Travel time in the air and on the ground (taxiing) is also tracked. Hourly request for runway use is also compared with actual hourly aircraft arrivals and departures with the hourly number of aircraft processed. Most of the statistics can be broken down by airline, runway, and/or gate. When comparing airport and airspace improvement alternatives, SIMMOD can be used to identify and quantitatively evaluate the various impacts on capacity and delay. It also provides a 2D animation and playback interface that allows planners to see the simulation unfold and to investigate specific problems.

2.2.2 Event Files

Event files are lists of arriving and departing aircraft operations. Each record (line) of an event file, contains a movement ID, an airline and flight number, a movement time, an aircraft type, a direction (arrival and departure), the airport at which the aircraft lands or takes off, a market served (last airport for an arrival or next airport for a departure), an air route used, and the gate or apron at which the flight starts or ends. The movement time is the scheduled departure time, but for an arrival it is the time at which the aircraft enters the airspace of the model. This last time is the scheduled arrival time minus the time it takes to fly through the model airspace, land and taxi to the gate without any delay.

There are two ways of specifying the event file: either as a list of independent flights (as if every flight represented a separate physical aircraft), or with some connected flights (where a specific departure is the same physical aircraft as a specific arrival). In the first case, no matter how bad arrival delays are, the departing flights will leave their gate at their scheduled time. In the second case a connected flight cannot depart until it has first arrived and spent a minimum turnaround time at the gate (depending on the aircraft type).

The second case is more realistic, especially when airports experience lengthy arrival delays as is the case at SFO during bad weather conditions (known as Instrument Flight Rules, or IFR). This approach was used for all the cases simulated in this study.

2.2.3 Airspace Structure and Separation Rules

SIMMOD defines the airspace structure as a set of links and nodes, with each air route composed of a series of connected links. The nodes are fixes, i.e. navigational aids (navaids) such as VORs, VORTACs, DMEs, and NDBs, or intersections of radials from these navaids. Aircraft assigned to a specific route progress from node to node along the links that define that route.

How an aircraft is released from the node at the start of a link is determined by the strategy chosen, and by local parameters such as link capacity and link aircraft speed type. The simplest strategy assumes that the link and its end node have sufficient capacity and therefore that aircraft are released from the first node as soon as they arrive, provided they do not violate the default ATC separation rules. More complex strategies look ahead to the next node to see how many aircraft are already there and whether there is room left for another one, while taking into account the number of aircraft already on their way.

SIMMOD can also slow down an aircraft (within the limits of acceptable speeds for that aircraft type on that link type) and/or delay its release time if the preceding aircraft is slower, so that by the time it arrives at the end node the separation minimum is not breached.

When two links merge into one, different merging strategies are also available: The merging node can just accept aircraft on a first come, first served basis. Or, it can slow down aircraft on one link while speeding up those on the other link so that seamless merging occurs; it can even select aircraft from each link so as to minimize the required separation. For example, on final approach, an aircraft sequence Heavy – Small – Heavy – Small would require 15 miles of the link, while the sequence Heavy – Heavy – Small – Small would require only 13.5 miles. ("Heavy" and "small" refer to aircraft weight categories.)

In general, the alternatives simulated in the study are based on the more complex strategies, because they tend to be more realistic, meaning they more closely replicate how the FAA actually manages the airspace.

2.2.4 Runway and Taxiway Structure

The arriving air routes end at the runway edge (interface), and start at the runway end for departures. The ground structure is defined by the links and nodes that connect these interface points with the terminal's gates (and/or apron positions) via the network of runways/exits/taxiways/taxilanes.

For arriving aircraft, as soon as the landing roll is completed SIMMOD looks for the nearest exit. If the exit is a high-speed exit (30 degree or less) and the aircraft's own speed has dropped to 60 knots or less, then the aircraft can use the exit. However for the other types of exits, the aircraft's speed must drop to nearly zero. From there, the program computes the route that gives the minimum time to the destination gate or apron position, based on link attributes such as maximum speed, aircraft type allowed, passing option, occupancy by other aircraft and capacity limit. If an airport has a circulation plan that mandates the use of specific taxiways for different aircraft types, then an override taxipath can be added in the event file for those aircraft that are affected.

For departing aircraft, the program computes the optimum route in a similar fashion: from the gate to the departure queue of the corresponding runway. When the aircraft has reached the head of the queue and is given the clearance to take-off, it completes the take-off roll and by the time it crosses the end threshold (i.e. by the time it is airborne) it is passed to the airspace structure via the interface point.

More that one departure queue can be assigned to a given runway in order to serve aircraft coming from different aprons of the airport. However delay can occur when taxiing aircraft have to cross an active runway, because all the time and distance separations from the table of runway procedures must be met before the aircraft can be given runway crossing clearance.

2.2.5 Runway Procedures

This procedure specifies for each operation and aircraft weight group what other operation and aircraft weight group it will block and for how long. For example, at SFO, a heavy aircraft on final for 28R, will block departures on 1L and 1R from two nautical miles (nm) away from the threshold (in VFR) until it has crossed the intersecting runways 1L and 1R.

A departing heavy aircraft on 1R will block any other aircraft from departing on 1R until a separation of 5 nm is achieved, due to the wake vortex separation rule. The same departure by a heavy on 1R should clear the 28R and 28L intersections before arrivals bound for these runways have crossed their corresponding threshold. If an approaching aircraft should cross the threshold of 28R or 28L before the departing aircraft has crossed the corresponding runway, it would have to abort landing and execute a missed approach procedure. This occurs only very rarely because the two nautical mile rule generally allows enough time for the departing aircraft to clear the intersection.

San Francisco International Airport, with its two pairs of intersecting runways, requires a relatively complex set of air traffic control procedures. To maximize runway capacity in good weather conditions (VFR) with westerly winds, the aircraft of the two streams of arrivals heading for 28R and 28L must be paired together on final approach. In other words, two aircraft have to fly more or less side by side, with the next pair following about 4 nm behind.

This separation allows enough time for two departing aircraft on 1L and 1R to take off as soon as the landing aircraft have crossed the departing runways, and for the next two landing aircraft to pass the threshold of their runway after the departing aircraft have cleared the intersections.

SIMMOD is capable of modeling this pairing process, which is necessary to model SFO accurately.

2.3 DEFINITION OF AIRSPACE AND AIRFIELD CAPACITY AND DELAY

Capacity is a measure of processing capability and is quantified by the number of aircraft operations that can be processed during a specific unit of time, such as an hour or an entire year. Delay is calculated in terms of average minutes of delay per aircraft arrival and/or departure during various weather conditions, using Instrument Flight Rules (IFR) procedures or Visual Flight Rules (VFR) procedures.

The “ultimate” capacity of an airfield system is the theoretical maximum number of continuous aircraft operations that an airfield can accommodate during a specified interval of time. On a practical level:

- Airfields experience peaking patterns where two or more aircraft often need to use the airfield at the same time, which will result in at least one aircraft experiencing slight delays.
- During peak periods, demand may exceed capacity; in these cases the aircraft will queue and wait until a landing or takeoff slot is available.
- It is rare for flights from all over the world to approach or depart an airspace in perfect and continuous sequence without any delay.

Thus, delays can determine the capacity of an airfield and an airspace network. Practical capacity is the number of aircraft operations that can be accommodated during a specific interval of time corresponding to a tolerable level of average delay. Acceptable flight delay may vary between different airports, but experts in the aviation industry agree that facilities and airspace can perform adequately with an average annual delay of 3 to 5 minutes maximum per aircraft.

“Experience shows that delay increases gradually with rising levels of traffic until the practical capacity of an airport is reached, at which point the average delay per aircraft operation is in the range of 3 to 5 minutes. Delays increase rapidly once traffic demand increases beyond this

level. An airport is considered to be congested when average delay exceeds 5 minutes per operation. Beyond this point delays are extremely volatile, and a small increase in traffic, adverse weather conditions, or other disruptions can result in lengthy delays that upset flight schedules and impose a heavy workload on the air traffic control system."[1]

Source: U.S. Department of Transportation, Federal Aviation Administration, Report to Congress, *National Plan of Integrated Airport Systems (1998-2002)*, March 1999

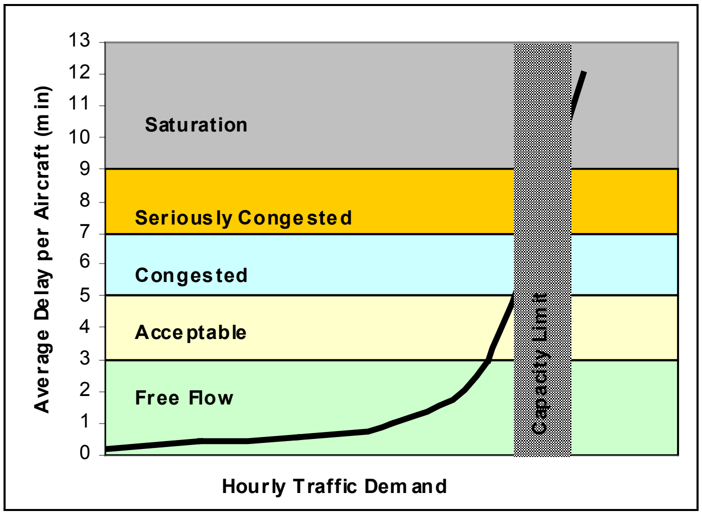

Figure 2-2 Influence of Aircraft Delay on Airfield Capacity

Delays above 5 minutes affect airline schedule integrity and can create extensive passenger inconvenience when flights are cancelled or diverted. When the airport is operating at reduced capacity, a large share of all arriving flights will be delayed or cancelled, and delays can typically average an hour or more, with frequent flyers routinely experiencing two to three hour delays. It should be pointed out that "modeled" delays are not directly comparable to other commonly quoted delay statistics from the FAA and Bureau of Transportation Statistics. These data track airline on-time performance and delays throughout the national airspace system, whereas this analysis focuses exclusively on what happens within the Oakland air route center airspace extending out about 150 nm. Delay information for Bay Area airports is summarized in the appendix using FAA CODAS data for 1997 and 1998.

2.4 FACTORS AFFECTING DELAY ON RUNWAYS AND AIRSPACE

Aircraft and passenger delays occur for many reasons. In Section 2.3, the definition of delay was provided. In this section, the factors affecting delay are presented and discussed. The purpose of this discussion is to orient the reader on the causes of airport delay. The following four factors have the most significant impact on delay:

[1] Federal Aviation Administration Report to Congress, *National Plan of Integrated Airport Systems (1998-2002),* March, 1999, at 10.

- Weather Conditions – Weather at the airport, especially as it affects visibility
- Airfield Layout –Configuration of runways (parallel, intersecting or combinations)
- Fleet Mix – Mix of aircraft, by size and type, using the airport
- Traffic Peaks – Periods when traffic volumes reach high points during the day

Of the four factors, weather has the most significant effect. It also directly impacts the other factors because it determines the rules under which aircraft are operated. Better understanding of all these factors will help to identify the source of delays at Bay Area airports, and to develop solutions to relieve congestion.

2.4.1 Weather Conditions

Weather affects airport operations in a number of ways. Wind direction and strength combined with visibility conditions (range and ceiling) require different runway use combinations and result in different airport capacities at the three Bay Area airports. While wind may change the direction of aircraft operations, it generally does not inhibit capacity. However, SFO normally has aircraft arrive on runways 28L and 28R and depart on 1L and 1R except when westerly winds exceed 20 nm per hour. In this condition, runways 1L and 1R cannot be used for departures. All aircraft must then use runways 28L and 28R for arrivals and departures, reducing SFO from four runways to two. This occurs at SFO between 7% and 10% of the time.

Visibility has a significant effect on capacity and defines the two main weather-related conditions under which aircraft operate. These are visual flight rules (VFR) and instrument flight rules (IFR). In good weather, skies are clear and VFR is in effect, typically allowing simultaneous use of close parallel runways because pilots can see nearby aircraft. When the cloud ceiling is low and visibility is poor, however, IFR is in effect and aircraft require greater separation. Under IFR conditions with closely spaced parallel runways (less than 4,300 feet separation or 3,400 under certain conditions), only one runway can be used. Since this is the situation with SFO, only a single runway can be used for arrivals during IFR conditions.

Table 2-1 shows the proportion of VFR to IFR conditions for the three Bay Area airports. SFO is affected the most by weather, which often means that the airport loses one of its two landing runways, thereby cutting the capacity from a maximum of 60 arrivals per hour to 30 or less per hour.

Table 2-1
Percentage of Visibility Conditions

	VFR (Good Weather)	IFR (Bad Weather)
San Francisco	80.0%	20.0%
Oakland	79.5%	20.5%
San Jose	85.0%	15.0%

Source: San Jose International Airport Master Plan, Draft 1996.

Bad weather is typically the main cause of delay at Bay Area airports. There are two types of bad weather that affect operations: 1) Bad weather in the morning during the summer due to low ("stratus") clouds, and 2) Bad weather all day, usually in the winter, due to seasonal storms with gusting southeasterly winds.

While bad weather mornings are about twice as frequent as bad weather all day, there is a greater chance of flight cancellations when weather is bad all day. When the weather is bad only in the morning, the airport has a chance to recover with delayed flights (similar to recovery following peak periods described in Section 2.4.4). When the weather is bad all day, the airport is often unable to accommodate all of the scheduled flights, leading to cancellations or diversions.

SFO's recent analysis shows that:

- On good weather days, 83% of the flights arrived on time (within 15 minutes of their scheduled arrival time)
- On days when weather was bad in the morning, 67% of the flights arrived on time
- On days when weather was bad all day, only 48% of the flights arrived on time[1]

Also, with poorer weather, more flights are cancelled, ranging from an average of 2% on good weather days to about 10% on days when the weather is bad all day.[1]

2.4.2 Runway Layout

The capacity of an airfield is determined in part by its configuration. Once a runway's capacity is exceeded, the airfield begins to experience delays. Two layout characteristics are the primary determinants of capacity. These are lateral spacing (between parallel runways) and intersecting runways. Other airfield characteristics that affect capacity are location of high speed exits, and taxiway configuration. The two major runway layout characteristics are:

Lateral Spacing – San Francisco currently has two pairs of parallel runways with each pair spaced 750 feet, which is adequate for simultaneous landings and takeoffs in VFR.conditions. San Francisco does not have adequate separation, however, under IFR conditions for independent simultaneous operations, as shown in the standards in Table 2-2.

[1] "Reducing Weather Related Delays and Cancellations at San Francisco International Airport," Charles River Associates and John F. Brown Company, April 2000.

Table 2-2
Runway Separation Standards Using IFR for Parallel Streams

Operation	Minimum Separation
Simultaneous approaches	4,300 feet
Simultaneous approaches (radar) *	3,000 feet
Simultaneous departures (non-radar)	3,500 feet
Simultaneous departures (radar) **	2,500 feet
Simultaneous approach and departure	2,500 feet

*Under consideration by FAA with high update radar and monitoring equipment.
** When the departure tracks diverge by at least 15^{o} on each side, simultaneous departures in IFR are possible even for runways as close as 750 feet.

Oakland and San Jose do not currently have parallel runways, but San Jose has one under development, and Oakland has future plans that include a new parallel runway. A narrower runway separation limits aircraft throughput, especially for arrivals and under IFR conditions. Wider runway separation allows for more operational flexibility and therefore a higher capacity. If runway thresholds are staggered, separation may be reduced or increased, depending on the amount of stagger and which runways are used for arrivals and departures. FAA provides complete guidelines for runway separation.

Intersecting Runways – When runways intersect, the throughput is limited by the obvious need to coordinate the cross traffic. The capacity of intersecting runways is dependent upon the location of the intersection; the manner in which runways are operated for takeoffs and landings (known as the runway use strategy); and the aircraft mix. The farther the intersection is from the takeoff end of the runway and the landing threshold, the lower the capacity. The maximum capacity is achieved when the intersection is close to the takeoff and landing threshold.

With two intersecting runways, departures are typically held on one runway, while an arriving aircraft lands on the intersecting runway. This dependent operation can be further complicated when a runway intersects parallel runways or more so when two sets of parallel runways intersect. In this case, operations must be synchronized into arrival pairs and departure pairs to maximize the window for intersecting traffic. In the case of the three Bay Area airports, only SFO has intersecting runways; OAK and SJC do not.

2.4.3 Fleet Mix

The fleet mix at a given airport affects the flow of departure and arrival streams due to the varying characteristics of different aircraft and their impact on one another. Standards for minimum separation (headway) between arriving and departing aircraft must be met; this limits the flow of operations and hence is a factor affecting delay. Size, based on weight, determines the minimum separation between aircraft. Smaller aircraft must have adequate separation behind larger aircraft due to the wake turbulence created by the larger aircraft. Table 2-3, below, is a definition of the four aircraft groups FAA has designated to determine aircraft separation. The B757 is in its own category because its weight places it in the “Large” category, however its wake characteristics are like a "Heavy" aircraft. Table 2-3 shows typical aircrafts that are representative of these categories.

Table 2-3
Aircraft Categories for Wake Separation

Heavy	Gross weight greater than 300,000 lbs. – B747, Airbus 340
B757	B757
Large	Gross weight greater than 12,500 lbs. but less that 300,000 lbs. – B737, Airbus 320
Small	Gross weight less than 12,500 lbs. – Citation II, Beech Baron

In an arrival stream, the order in which aircraft of different weights are allowed to approach must be considered. Using the aircraft categories above, final approach wake turbulence separation, measured in nautical miles, is determined by the order of the arriving aircraft. In a departure stream, the order in which aircraft of different weights are allowed to takeoff must be similarly considered. Also, the mix of turboprops and jets is another factor determining departure separation, since turboprops climb in altitude more slowly than jets do. Greater separation must be provided between a jet following a turboprop, in order to give the turboprop sufficient time to reach the point at which it leaves the jet route.

As an example of the application of these rules, for San Francisco, the separations presented in Table 2-4 are followed. This table shows separations within 10 nautical miles of the airport and in the larger airspace (general) as well as in VFR and IFR conditions.

Table 2-4
Minimum SFO Trailing Aircraft Separations (in nautical miles)

		Trailing Aircraft							
		Final Approach (within 10 nm)				General			
Conditions	Leading Aircraft	Heavy	B757	Large	Small	Heavy	B757	Large	Small
Visual Flight Rules	Heavy	2.9	3.6	3.6	4.5	4.0	4.0	5.0	5.0
	B757	2.9	2.9	2.9	3.7	4.0	4.0	4.0	5.0
	Large	2.5	2.5	2.5	2.7	4.0	4.0	4.0	4.0
	Small	2.5	2.5	2.5	2.5	4.0	4.0	4.0	4.0
Instrument Flight Rules	Heavy	4.0	4.0	4.0	6.0	4.0	4.0	5.0	5.0
	B757	4.0	4.0	4.0	5.0	4.0	4.0	4.0	5.0
	Large	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
	Small	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0

2.4.4 Traffic Peaks

As mentioned above in discussing runway layout, every airfield has capacity limits. When that capacity is exceeded, delays result. During peak periods, the airfield capacity may be exceeded for a brief or sustained period depending on the peak's duration. In the case of a brief or sustained peak, a queue begins to form which results in delay. For a shorter peak, the queue will begin to dissipate in the time following, and delays will decrease as the volume reduces back to or below capacity. For a more sustained peak, however, the recovery time is much longer and the delays persist. Sometimes, the impact of a long peak has a ripple effect that can be felt throughout the day. If there are significant peaks that begin to overlap, the airport may experience a low level of service and not recover all day.

Figure 2-3 illustrates what happens when capacity is exceeded during most of the day. The upper curve is the cumulative demand curve, i.e., aircraft arriving in the airport area since midnight. The lower curve is the cumulative number of aircraft that have been processed (landed). For an aircraft arriving at 1800 (6 p.m.), the tower may tell the pilot "you are number 420 and we are currently serving number 320. Your estimated landing time will be about 2200 (10 p.m.)". This implies a four hour delay. This figure also shows that once capacity is exceeded, the delays just keep growing.

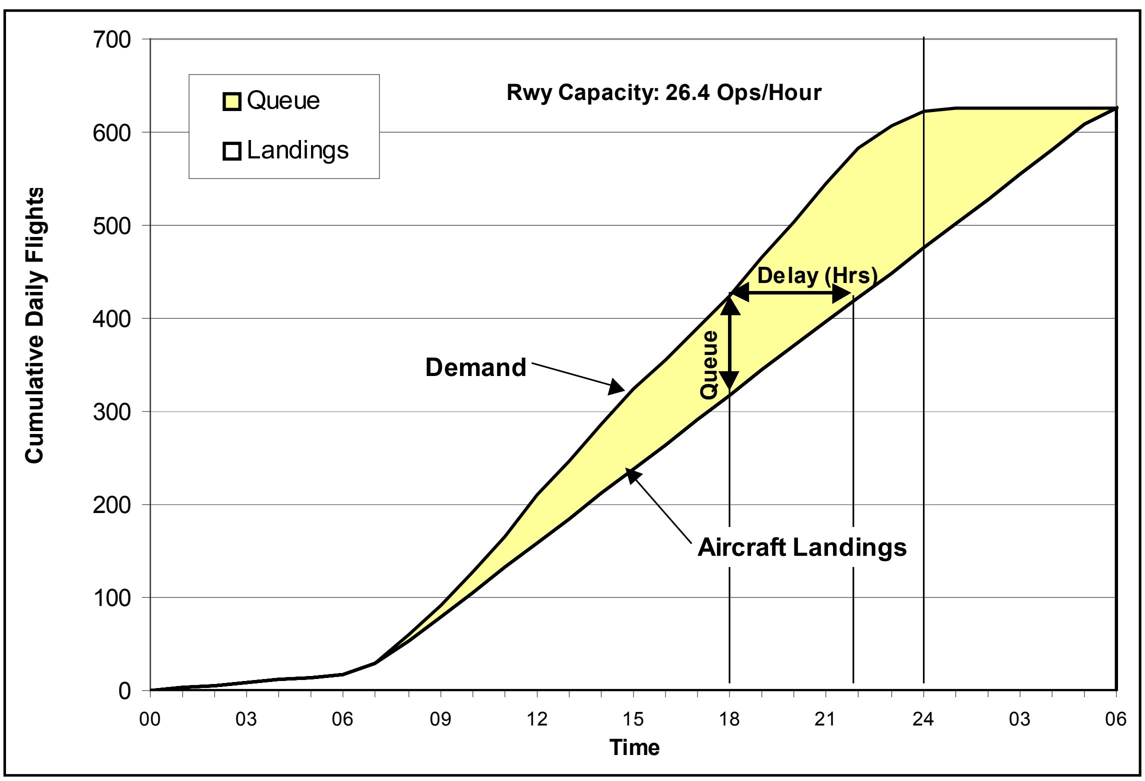

Figure 2-3 Build-up of Queue Length when Demand Exceeds Capacity